CORRESPONDENCE

Comments on "Why Hasn't Earth Warmed as Much as Expected?"

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ABSTRACT

In a recent paper, Schwartz et al. suggest that 1) over the last century the earth has warmed less than expected, and they discuss several factors that could explain the discrepancy, including climate sensitivity estimates and aerosol forcing. Schwartz et al. then continue to 2) estimate the allowed carbon emissions for stabilization of global temperature, and find that given the uncertainty in the climate sensitivity even the sign of these allowed carbon emissions is unknown, implying that past emissions may already have committed the earth to 2°C warming for a best-estimate value of climate sensitivity of 3 K. Both of these conclusions in the Schwartz et al. study are revisited herein, and it is shown that 1) in contrast to Schwartz et al., current assessments of climate sensitivity, radiative forcing, and thermal disequilibrium do not support the claim of a discrepancy between expected and observed warming; and 2) the allowed emissions estimated by Schwartz et al. are in conflict with results from a hierarchy of climate–carbon cycle models and are strongly underestimated due to erroneous assumptions about the behavior of the carbon cycle and a confusion of the relevant time scales.

1. The relationship between climate sensitivity, radiative forcing, and the observed warming

In the first part of their paper, Schwartz et al. (2010, hereafter S10) discuss the relationship between the expected equilibrium warming from long-lived greenhouse gases (GHGs), radiative forcing, and climate sensitivity. With the title of their paper "Why hasn't Earth warmed as much as expected?" and an introductory statement that "the observed increase of global mean surface temperature over the industrial period is less than 40% of what would be expected from present best estimates of the earth's climate sensitivity and the forcing by the observed increases in GHGs," S10 create the impression of conflicting evidence between theory and models on the one hand, and observations on the other hand. They go on to study the factors that could contribute to this "discrepancy," for example, "current estimates of climate sensitivity being too high."

We argue that the presentation of the results by S10 is misleading and the conclusions drawn are unsupported. Uncertainties do not make discrepancies. If all radiative forcings (including the negative contributions from aerosols) and the imbalance of the climate system and their respective uncertainties are properly taken into account, there is no discrepancy between predicted and observed warming. Comprehensive general circulation models (e.g., Stott et al. 2000; Meehl et al. 2004), intermediate complexity climate models (e.g., Forest et al. 2002; Knutti et al. 2003), and simple climate models (e.g., Meinshausen et al. 2009) all simulate warming that is entirely consistent with observations if all radiative forcings are considered. Climate sensitivity is poorly constrained from the observed surface warming and ocean heat uptake (which is evident from Fig. 3 of S10, and noted later in their discussion). Already 25 years ago, Wigley and Schlesinger (1985) concluded, based on an analytical model, that because the lag of surface temperature to the forcing and the degree of disequilibrium are strongly dependent on the ocean mixing

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and climate sensitivity, "the observed global warming over the past 100 years can be shown to be compatible with a wide range of CO_2 doubling temperatures." In a probabilistic study with an intermediate complexity model in 2002, Knutti et al. (2002) concluded that "given the uncertainties in the radiative forcing, in the temperature records, and in currently used ocean models, it is impossible at this stage to strongly constrain the climate sensitivity." More than a dozen papers over the last decade or so have looked at this problem in a comprehensive way with climate models of different complexities. Most of these studies have calculated uncertainty ranges and probability density functions for climate sensitivity (Andronova and Schlesinger 2001; Forest et al. 2002; Gregory et al. 2002; Harvey and Kaufmann 2002; Knutti et al. 2002, 2003; Frame et al. 2005; Allen et al. 2006; Forest et al. 2006; Forster and Gregory 2006; Tomassini et al. 2007; Knutti and Hegerl 2008; Meinshausen et al. 2009; Sokolov et al. 2009; Urban and Keller 2009) based on a combination of the observed surface warming, ocean heat uptake, and radiative forcing. Several of the above studies include much more rigorous methods for estimating uncertainties than those of S10, and have used either the time evolution of the forcing and response or the patterns of the warming to constrain climate sensitivity. They do not find discrepancies between the observed warming and the expected warming from estimates of radiative forcings if the published uncertainties in forcing, feedbacks, and ocean heat uptake are properly considered.

S10 speculate in their discussion that climate sensitivity may be lower than currently thought. It is interesting to note that until a few years ago parts of the aerosol community have argued for a magnitude of the aerosol forcing that is larger (i.e., more strongly negative than about -2 W m^{-2}) than the values consistent with the energy budget (Anderson et al. 2003; Lohmann et al. 2010). Such strong aerosol forcings would in fact favor climate sensitivities far above (rather than below) the current best estimate of 3 K. Constraints from the observed warming suggested that values for the total aerosol effect exceeding from -1 to -2 W m^{-2} (depending on the climate model and the uncertainties assumed for other forcings) would result in a net forcing that is too small to account for the observed warming (e.g., Knutti et al. 2002; Anderson et al. 2003). Direct estimates from process-based aerosol models, on the other hand, were centered around -1.5 W m^{-2}, with some uncertainty ranges exceeding -3 W m^{-2} (Anderson et al. 2003). More recent estimates of the aerosol forcing tend to be less negative (e.g., Quaas et al. 2006; Lohmann et al. 2010), although the uncertainty is still large.

The large body of work on climate sensitivity discussed above and summarized in a recent review (Knutti and Hegerl 2008) is complemented by the analysis of feedbacks (e.g., Bony et al. 2006; Roe and Baker 2007; Gregory et al. 2009), observed greenhouse gas attributable warming or total warming, and the greenhouse gas relation to the transient climate response or warming for realistic scenarios (Allen et al. 2000; Stott et al. 2006; Stott and Forest 2007; Knutti 2008; Knutti et al. 2008b; Knutti and Tomassini 2008), as well as the observed and simulated energy budget (Hansen et al. 2005; Murphy et al. 2009). We therefore argue that the relation between forcings, feedback, climate sensitivity, and observed warming, as well as their implications for future warming, are well understood and quantified, and that different lines of evidence are all consistent within their uncertainties. We do not see any indication for a "discrepancy" that needs to be explained and argue that the analysis by S10 provides little insight into the problem beyond what is already well established.

2. Allowed carbon emissions for stabilization of global temperature

a. *Time scales and reservoirs in the carbon cycle and climate system*

In the second part of their paper, S10 present a simple calculation of the allowed carbon emissions that would be consistent with stabilization of global temperature at different levels and for different climate sensitivities. They conclude that "current uncertainty in climate sensitivity is shown to preclude determining the amount of future fossil fuel CO_2 emissions that would be compatible with any chosen maximum allowable increase in global mean surface temperature; even the sign of such allowable future emissions is unconstrained." For example, S10 find that if carbon emissions were stopped altogether today, historic emissions would commit us to a warming of 2.1 K above preindustrial levels for the current best estimate of climate sensitivity of 3 K (Knutti and Hegerl 2008). In other words, the widely discussed goal of limiting global temperature increase to 2 K above preindustrial levels would be unfeasible even if all emissions were stopped today. Here we show that the calculations by S10 are based on two obvious errors that entirely invalidate their conclusions.

The simple calculations are based on the following definitions and relationships. The climate sensitivity parameter is defined as the ratio $\Delta T/\Delta F$ between temperature change ΔT and radiative forcing ΔF, and climate sensitivity S (the equilibrium global mean surface temperature change for doubling of the atmospheric CO_2 concentration) is defined as $S = \Delta T/\Delta F \times 3.7$ W m^{-2}, where 3.7 W m^{-2} is the radiative forcing for CO_2 doubling. The additional radiative forcing from a CO_2 concentration c is given by $\Delta F = 5.35\ \mathrm{W\ m^{-2}} \times \ln(c/280\ \mathrm{ppm})$, with 280 ppm being the preindustrial CO_2 concentration. An additional 2.1 Gt of carbon (GtC) added to the atmosphere increase the atmospheric concentration by 1 ppm if no other sinks are present.

The first error is that S10 assume an equilibrium state of the carbon budget today. They incorrectly assume that the current forcing for long-lived GHGs of 2.6 W m^{-2} [a value consistent with that of the Intergovernmental Panel on Climate Change (IPCC; Forster et al. 2007)] would remain constant if emissions were stopped. This would correspond to an equivalent CO_2 concentration today of 455 ppm, and therefore already exceed the canonical value of 450 ppm that is often quoted for the stabilization of temperature below 2 K. In reality, however, the atmospheric CO_2 concentration would drop if emissions were stopped completely. In a recent study, Solomon et al. (2009) estimated that the quasi-equilibrium enhancement of CO_2 concentration above its preindustrial value is 40% of the peak enhancement. The current CO_2 concentration is about 380 ppm, that is, about 100 ppm above preindustrial levels, of which about 40 ppm would therefore remain in the atmosphere in quasi equilibrium (i.e., about 1000 yr) after halting emissions; the rest is taken up by the other fast-responding, that is, on decadal to millennial time scales, carbon reservoirs ocean and terrestrial biosphere. The non-CO_2 greenhouse gas forcing (about 75 ppm CO_2 equivalent, mostly from methane and N_2O) and aerosols would probably be eliminated to a large extent as well if emissions of CO_2 were stopped, but different assumptions are possible and three illustrative cases are thus shown below. Note that methane and N_2O have lifetimes of about 10 and 150 yr, respectively. Therefore, if emissions were stopped, most of their radiative forcing would be eliminated on time scales of centuries that are relevant for temperature stabilization.

To illustrate the effect of zero carbon emissions today, results from the Bern2D intermediate complexity carbon cycle–climate model for a zero emission scenario are shown in Fig. 1. The Bern2D model includes components describing 1) the physical climate system, 2) the cycling of carbon and related elements, and 3) a module to calculate concentrations of non-CO_2 GHGs and radiative forcing by atmospheric CO_2, non-CO_2 GHGs, and aerosols (Joos et al. 2001; Plattner et al. 2001). The model consists of a zonally averaged dynamic ocean resolving the Atlantic, Pacific, Indian, and Southern Oceans and is coupled an energy moisture balance atmosphere and a marine and terrestrial carbon cycle. The ocean biogeochemical component is a simple description of the cycles of carbon and carbon-related tracers (Marchal et al. 1998), with phosphate as the biolimiting nutrient for marine productivity. The carbon cycle component is complemented by a simple four-box representation of the terrestrial biosphere (Siegenthaler and Oeschger 1987) to account to first order for changes in terrestrial carbon storage under rising CO_2. Time series for all radiative forcings are prescribed until 2009, including a best estimate of the aerosol direct and indirect forcing, which results in a total forcing that is within 0.1 W m^{-2} of the best estimate given by the IPCC (Forster et al. 2007). The feedbacks are set to yield a climate sensitivity that is close to the current best estimate of 3 K (Meehl et al. 2007; Knutti and Hegerl 2008). The simulated past

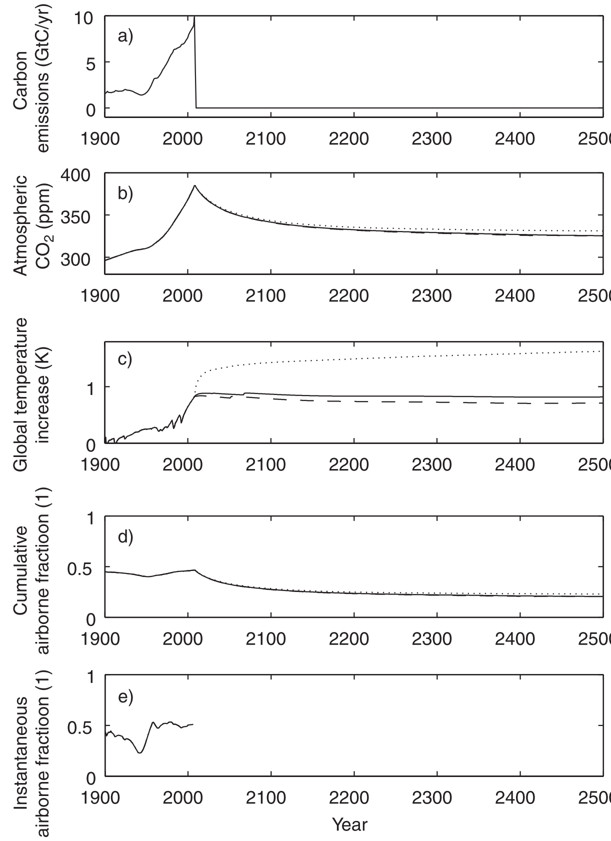

FIG. 1. Results from the Bern2D carbon cycle–climate model for prescribed historical carbon emissions until 2010 and zero future carbon emissions thereafter. The three cases shown are for non-CO_2 forcings that are constant after 2010 (default, solid line), non-CO_2 forcings set to zero (dashed line), and non-CO_2 GHG forcings constant and non-GHG forcings set to zero (dotted line). The models climate sensitivity is close to 3 K. The (a) anthropogenic carbon emissions, (b) atmospheric CO_2 concentration, (c) global temperature change since preindustrial levels, (d) cumulative airborne fraction, i.e., the ratio between increase in atmospheric carbon inventory since preindustrial levels and cumulative carbon emissions since preindustrial levels, and (e) instantaneous airborne fraction, i.e., the increase in atmospheric carbon inventory and carbon emissions at a given time (only defined for the time when emissions are nonzero) are shown.

warming of 0.8 K agrees well with observations. The setup of the model is very similar to earlier studies (Joos et al. 1999; Plattner et al. 2001). When CO_2 emissions are stopped (but all other forcings are kept constant), the atmospheric CO_2 concentration decreases and stabilizes at 325 ppm in year 2500, which is close to the 320 ppm estimated above (Solomon et al. 2009; see Fig. 1b, solid line). While the initial carbon uptake from the terrestrial biosphere and the surface ocean is relatively quick, the long-term response is dominated by the time scales of the deep-ocean carbon uptake, which are on the order of centuries. These ocean time scales can be estimated from the observed vertical distributions of anthropogenic heat (Levitus et al. 2000), carbon, chlorofluorocarbons (CFCs), and tracer perturbations (e.g., Sabine et al. 2002), as well as from models (e.g., Stouffer 2004; Knutti et al. 2008a). While some of the feedbacks between the carbon cycle and climate are still uncertain, there is clear evidence from many different models (Friedlingstein et al. 2006; Plattner et al. 2008; Gregory et al. 2009), as well as observations (Le Quere et al. 2009), that the ocean was the major sink for anthropogenic carbon up to today and will remain so in the future, with the deep ocean, and therefore the whole carbon budget, requiring many centuries to reach equilibrium.

The decrease in atmospheric CO_2 after halting emissions would imply cooling of the atmosphere, but this is almost exactly offset in our model setup by the commitment warming, that is, the fact that surface temperature has not yet equilibrated with the radiative forcing when emissions are switched off. The result is a near-constant temperature for several centuries as shown by the solid line in Fig. 1c. This behavior is remarkably robust over a range of at least 10 models of different complexity (Plattner et al. 2008; Matthews et al. 2009; Solomon et al. 2009; Frölicher and Joos 2010). In summary, our results demonstrate that S10 overestimate the committed warming for zero CO_2 emissions today by at least a factor of 2. With a best estimate of climate sensitivity of 3 K, zero CO_2 emissions would therefore likely lead to some cooling or near-constant temperature (Plattner et al. 2008; Solomon et al. 2009; Frölicher and Joos 2010), equivalent to the argument in recent studies that the warming per unit carbon emission is approximately constant (Allen et al. 2009; Matthews et al. 2009) over time and scenarios for one model, although the ratio itself is model dependent.

The model response obviously depends on the assumptions made for other forcings. Our default case reduces CO_2 emissions to zero but keeps all other forcings constant to avoid mixing the responses from different forcings with different time scales. If the focus is on the true temperature commitment of past emissions, then presumably all other forcings (including aerosols) would be eliminated along with CO_2 emissions. The temperature response in this case is nearly identical because the non-CO_2 forcings nearly compensate (Fig. 1b, dashed line). The strongest warming results if the aerosol forcing is eliminated but non-CO_2 greenhouse gases are kept constant. In this case global temperature increases above present levels but still remains well below 2° (Fig. 1, dotted lines). Further details regarding time scales are discussed below. The treatment of non-CO_2 greenhouse gases by S10 is not clear, but from their claim that "if the CO_2 doubling temperature of the earth's climate is 3 K, *an immediate cessation of emission of CO_2 and other GHGs* would be required for the equilibrium temperature increase above preindustrial not to exceed 2 K" (emphasis added), we assume that non-CO_2 greenhouse gases are also set to zero in their calculation. Whatever assumption is made, the results in Fig. 1 show that the above claim by S10 is not supported by our model.

The second error by S10 is that they use an airborne fraction of 0.5 for temperature stabilization in their simple calculation, implying that 50% of the anthropogenic carbon would remain in the atmosphere in equilibrium. Indeed about 50% of the anthropogenic emissions every year are taken up by the ocean and terrestrial biosphere (e.g., Knorr 2009; Le Quere et al. 2009), but this is an instantaneous airborne fraction, that is, the ratio between atmospheric increase and anthropogenic emissions for a given point in time. However, the relevant quantity for stabilization is the cumulative (or equilibrium) airborne fraction, that is, the ratio between the total cumulative carbon remaining in the atmosphere and the total emissions after the system has equilibrated. The equilibrium airborne fraction on a time scale of centuries to a millennium is 20%–25%. Figure 1 shows that the Bern2D model reproduces this well. As long as emissions continue to increase, both the instantaneous and cumulative airborne fraction are about of 50%. However, when emissions stop, the ocean and biosphere continue to remove excess carbon from the atmosphere. The cumulative (or equilibrium) airborne fraction in this model is 20% at year 2500, consistent with a many earlier studies. For example, Archer et al. (2009) calculate an equilibrium airborne fraction for 1 Pg of carbon (1 PgC = 1 TtC; this is a rough estimate for 2-K warming) after 1000 yr of about 20%, with a model spread of about ±5%. Plattner et al. (2008) similarly find an instantaneous airborne fraction of 50% and an equilibrium airborne fraction of 20% after 1000 yr based on a range of coupled carbon cycle climate models. For much larger emissions the equilibrium airborne fraction can be larger, for example, 25% for about 1.7 PgC (Plattner et al. 2008). Note that by definition, because stabilization is about equilibrium, the equilibrium quantities are relevant. It is inappropriate to use climate sensitivity (which is an equilibrium value) and combine it with a transient airborne fraction. In summary, a large number of studies using climate–carbon cycle models of different complexities demonstrate that the airborne fraction of 50% assumed by S10 is too large by about a factor of 2 for the time scale that is relevant for stabilization.

b. *Implications for allowed carbon emission*

S10 estimate the allowed carbon emission for different temperature stabilization levels and climate sensitivities. We reproduce their Fig. 4 in our Fig. 2a, assuming an airborne fraction of 0.5 and a commitment-equivalent CO_2 concentration from past emissions of 455 ppm, equivalent to the current GHG forcing of 2.6 W m^{-2}. The same simple estimate but with more appropriate values of committed CO_2 of 320 ppm (40% of the current excess carbon) and an airborne fraction of 0.2 leads to the estimates shown in Fig. 2b. While this looks visually similar at first, the numbers we estimate are strikingly different. To demonstrate the validity of our argument, we calculated about 700 simulations with the Bern2D model and the setup as in Fig. 1. In agreement with the assumption by S10 we kept emissions constant at current levels and set them to zero at different times in the future. The shape of the emission pathway is largely irrelevant for this discussion because the warming is determined by cumulative emissions (Allen et al. 2009; Matthews et al. 2009). All non-CO_2 forcings were kept constant at current levels until the end of the simulation, but again this is not important for stabilization because the positive non-CO_2 GHG forcings are approximately canceled by the cooling of the aerosols. Simulations where all non-CO_2 forcings are set to zero show almost identical results for equilibrium. Figure 2c shows that the results from the Bern2D model are in good agreement with our revised simple estimate. We emphasize that the results in Fig. 2c based on the carbon cycle–climate model make no a priori assumption about time scales, temperature lags to forcing, disequilibrium, or the airborne fraction. All quantities, including the full carbon budget, are determined by the model, and only the climate sensitivity and

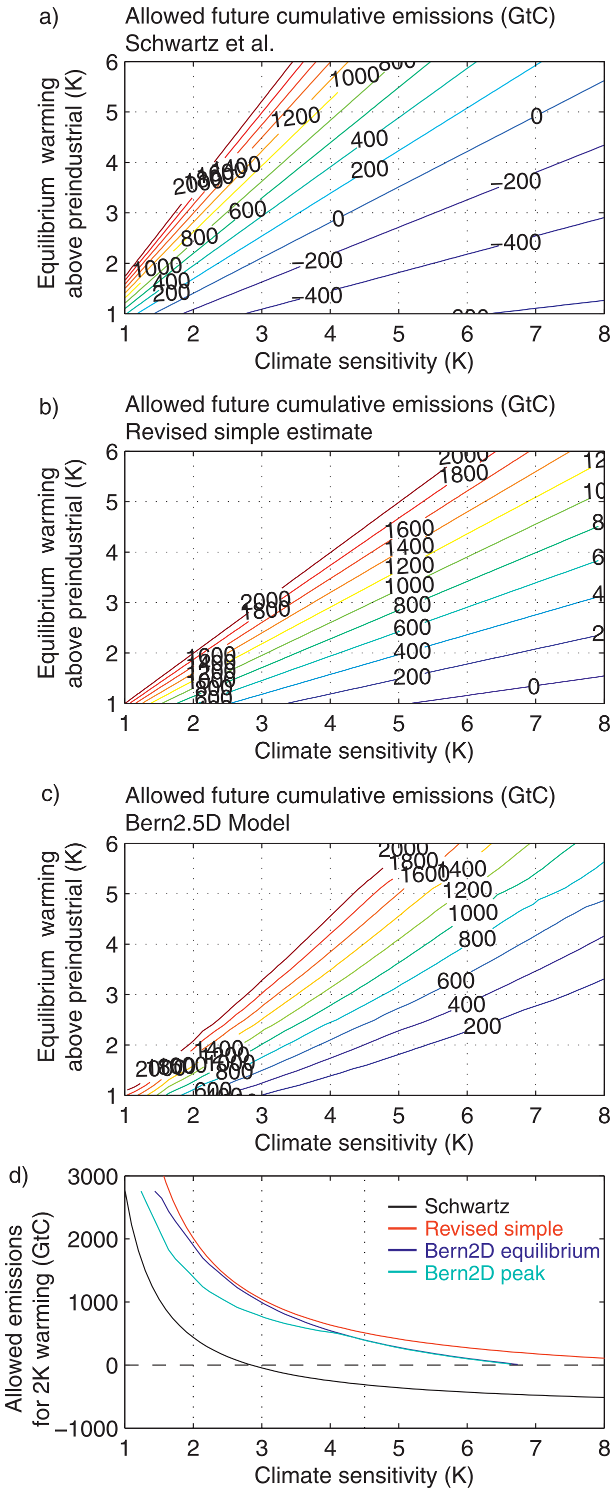

FIG. 2. (a) Allowed future cumulative carbon emissions calculated for different climate sensitivities and global temperature stabilization targets as estimated by S10 (their Fig. 4); (b) as in (a), but revised using correct values of equilibrium airborne fraction of 0.2 and considering the current imbalance in the carbon budget (see text); (c) as in (a), but estimated from about 700 simulations with the Bern2D coupled carbon cycle–climate model; and (d) allowed future cumulative carbon emissions for different climate sensitivities and a stabilization target of 2 K for the method by S10 [black, from (a)], the revised simple estimate [red, from (b)], and the Bern2D model for equilibrium warming [blue, from (c)]. Limiting the peak warming (cyan) rather than the equilibrium warming to 2 K in the Bern2D model has a small effect. Non-CO_2 forcings are kept constant when carbon emissions are set to zero, but the conclusions are similar for other cases.

the anthropogenic carbon emissions are prescribed for each simulation.

To make the comparison easier we also show the allowed emissions for the often discussed warming target of 2 K as a function of climate sensitivity for the various assumptions (Fig. 2d). Again there is remarkable agreement between our revised simple estimate and the climate model, even if peak warming rather than equilibrium warming is considered. The results by S10, however, are in stark contrast to the model and strongly underestimate the allowed emissions. For sensitivities in the range of 3–6 K even the sign is different.

Several recent studies have quantified the allowed carbon emissions for temperature stabilization. Allen et al. (2009) find that ''total anthropogenic emissions of one trillion tonnes of carbon (3.67 trillion tonnes of CO_2), about half of which has already been emitted since industrialization began, results in a most likely peak carbon-dioxide induced warming of 2°C above pre-industrial temperatures.'' Similarly, Matthews et al. (2009) find a ratio of 1–2.1 K warming per petagram of carbon, so for the half a trillion ton emitted up to today we would expect a warming of 0.5–1 K, in good agreement with the results presented in Fig. 1. Warming of 2 K would imply cumulative emissions of about 1–2 PgC, in reasonable agreement with our model that estimates a range of about 0.5–2 PgC for the current likely range of climate sensitivity of 2–4.5 K. The allowed emissions estimated by Meinshausen et al. (2009) focus on the time period to 2050 but are also broadly consistent with those of Allen et al. (2009). In contrast, the method by S10 estimates allowed emission of -0.3 to $+0.3$ PgC for the same range of climate sensitivity. Allowed emissions depend, of course, on the response of the carbon cycle in a baseline climate (i.e., how much carbon is taken up by the ocean and biosphere without climate change) and the feedbacks between the climate and carbon cycle, as well as on the assumption about non-CO_2 forcings. However, there is agreement among different methods and models of various complexities that allowed emissions for 2-K warming between 0.5 and 2.5 PgC for climate sensitivities in the range of 2–4.5 K. The estimate of -0.3 to $+0.3$ PgC by S10 is inconsistent with all of the models of which we are aware.

Finally, temperature stabilization by definition refers to equilibrium (from centuries to millennia). In this case, the use of climate sensitivity and the equilibrium airborne fraction of about 0.2 are appropriate. If the focus, however, is on decadal changes, then indeed the airborne fraction of CO_2 is closer to 0.5, as assumed by S10, but then the relevant quantity to quantify the warming is the transient climate response (TCR) and not climate sensitivity. The best estimate of TCR is about 1.8 K (Stott et al. 2006; Gregory and Forster 2008; Knutti and Tomassini 2008), which is much smaller than the best estimate of climate sensitivity of 3 K (Knutti and Hegerl 2008). S10 erroneously combine equilibrium climate sensitivity relevant for stabilization centuries into the future with an instantaneous airborne fraction that is only meaningful for the present situation where the carbon reservoirs of ocean and atmosphere are not in balance.

3. Conclusions

S10 claim that the earth has not warmed as much as expected and create the impression of conflicting evidence between theory and models on one hand, and observations on the other hand. We argue that, in fact, there is no conflict at all, as long as all known forcings (including the negative contributions from aerosols) and the imbalance of the climate system and their respective uncertainties are properly taken into account. This is supported by a wealth of observational and modeling studies as demonstrated above. Furthermore, S10 argue that the ''current uncertainty in climate sensitivity is shown to preclude determining the amount of future fossil fuel CO_2 emissions that would be compatible with any chosen maximum allowable increase in global mean surface temperature; even the sign of such allowable future emissions is unconstrained.'' For the range of climate sensitivities they consider (1.5–5 K, their Fig. 4), this statement is incorrect. While the uncertainty in climate sensitivity obviously introduces a large uncertainty in the calculation of the allowed carbon emissions for temperature stabilization, we have demonstrated that the results obtained by S10 are based on erroneous assumptions. First, their simple calculation uses an equilibrium airborne fraction of 0.5 rather than 0.2. Second, it fails to account for the fact that the climate and carbon cycle is not in equilibrium with the current atmospheric CO_2 concentration forcing. The true commitment warming from past emissions is not given by the current CO_2-equivalent concentration, but by the fraction of excess carbon that would remain in the atmosphere in equilibrium when stopping emissions today. The latter is much smaller than the former. The analysis by S10 therefore strongly underestimates the allowed emissions, and erroneously concludes that even the sign of allowed future emissions for any temperature stabilization target is unconstrained. While very strong carbon emission reductions are obviously needed over the next century to stabilize the global temperature increase below for example 2 K, it is very unlikely that past emissions have already committed us to a warming of 2 K.

In summary, the calculations by S10 oversimplify the energy balance and carbon cycle, neglect relevant response time scales, and incorrectly combine equilibrium climate sensitivity with a transient value of the airborne fraction. Their results cannot be reconciled with those presented here based on the Bern2D intermediate complexity climate–carbon cycle model, or indeed with any of the zero emission–commitment or temperature-stabilization scenarios calculated by a climate model that resolves the relevant time scales and reservoirs of the energy balance and carbon cycle (Caldeira et al. 2003; Hare and Meinshausen 2006; Weaver et al. 2007; Matthews and Caldeira 2008; Plattner et al. 2008; Allen et al. 2009; Matthews et al. 2009; Meinshausen et al. 2009; Solomon et al. 2009; Zickfeld et al. 2009; Frölicher and Joos 2010; Rogelj et al. 2010; Solomon et al. 2010; Gillett et al. 2011).

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